Higgs and Precision Electroweak Interactions at the LHC

Low Energy Precision Electroweak Physics in the LHC Era

Sept. 29, 2008
I. Precision Electroweak
   A. W mass
   B. Anomalous gauge couplings
   C. Top quark

II. Higgs
   A. SM Higgs search
   B. Higgs properties measurements

III. A slide on the magnet incident
Definition of “Precision Electroweak”

- The Standard Model is remarkable, in that at tree level, only three parameters are needed to predict everything.
  - $G_F$, $\alpha$ and $\sin^2(\theta_w)$ would be one choice

- As well as measurements of those, precision electroweak measurements also attempt to look for deviations from the simple 3-parameter theory
  - Loop effects:
    
    $$m_W = 4 \sqrt{\frac{\pi^2 \alpha^2}{2G_F^2}} \frac{1}{\sin \theta_W \sqrt{1 - \Delta R}}$$

  - Couplings that differ from SM values
    - *i.e. evidence that three parameters are not enough*

“A Precision EWK” often just means “W Mass”. I won’t focus exclusively on that, and will devote more time for anomalous gauge couplings.
Status of the Simulation

- ATLAS released its Physics TDR in 1999 (!)
  - Since then
    - More up-to-date generators
    - Parametric simulation & GEANT3 replaced by GEANT4
    - Digitization allows for both in-time and out-of-time pileup
    - Misalignments and miscalibrations are supported
    - Reconstruction has gone through many release cycles
  - ATLAS continually releases updates on many TDR analyses throughout the past few years

I’m surprised the forthcoming and public numbers are not more different. Increasing realism is often just about balanced by more intelligent reconstruction and analysis.
I am not going to try and sell you on the idea that the LHC will reach a precision of 15 or 20 MeV. (It might … but don’t hold your breath.)

Instead, I want to outline some of the issues involved.
Rapidity – of getting $m(W)$ results published

The trend is for later runs to be on a curve which begins lower and to the right of earlier runs.

Precision results are much slower than searches!

No hadron collider experiment has published an uncertainty of 100 MeV in less than 1400 days.
**Measuring $m(W)$ – Why It Takes so Long**

- **Set Momentum Scale**
  - Use known states like $Z^0$, $J/\psi$, and $\Upsilon$ family
  - As this is done, removing tracking systematic problems:
    - *Misalignments, miscalibrations, twists, distortions, false curvatures, energy loss…*

- **Set Energy Scale**
  - Use electrons and “known” material and momentum scales

- **Recoil & Underlying Event Characterization**

- **Modeling, Modeling, Modeling**
  - Transverse mass vs. lepton $p_T$ vs. missing energy, QCD radiation, QED radiation, production models, underlying event, residual nonlinearities…

It’s not unusual for >1000 plots to appear in the (complete) set of internal notes for this analysis.
**Difficulty 1: The LHC Detectors are Thicker**

- Detector material interferes with the measurement.
  - You want to know the kinematics of the W decay products at the decay point, not meters later
  - Material modeling is tested/tuned based on electron E/p

- Thicker detector = larger correction = better relative knowledge of correction needed
Difficulty 2 – QCD corrections are more important

- No valence antiquarks at the LHC
  - Need sea antiquarks and/or higher order processes
- NLO contributions are larger at the LHC
- More energy is available for additional jet radiation

- At the Tevatron, QCD effects are already ¼ of the systematic uncertainty
  - Reminder: statistical and systematic uncertainties are comparable.
- To get to where the LHC wants to be on total $m(W)$ uncertainty is going to require continuous effort on this front.
**Major Advantage – the W Rate is Enormous**

- The W/Z cross-sections at the LHC are an order of magnitude greater than the at the Tevatron
- The design luminosity of the LHC is ~an order of magnitude greater than at the Tevatron
  - I don’t want to quibble now about the exact numbers and turn-on profile for the machine, nor things like experimental up/live time

**Implications:**
- The W-to-final-plot rate at ATLAS and CMS will be ~½ Hz
  - Millions of W’s will be available for study – statistical uncertainties will be negligible
  - Allows for a new way of understanding systematics – dividing the W sample into N bins (see next slide)
- The Z cross-section at the LHC is ~ the W cross-section at the Tevatron
  - Allows one to test understanding of systematics by measuring m(Z) in the same manner as m(W)
  - The Tevatron will be in the same situation with their femtobarn measurements: we can see if this can be made to work or not
- One can consider “cherry picking” events – is there a subsample of W’s where the systematics are better?
Systematics – The Good, The Bad, and the Ugly

**Good**

- Masses divided into several bins in some variable
- Masses are consistent within statistical uncertainties.

**Bad**

- Clearly there is a systematic dependence on this variable
- Provides a guide as to what needs to be checked.

**Ugly**

- Point to point the results are inconsistent
- There is no evidence of a trend
- Something is wrong – *but what?*
**W Mass Summary**

- ATLAS and CMS have set themselves some very ambitious goals in a 15 or 20 MeV W mass uncertainty
  - This will not be easy
  - This will not be quick
  - It potentially might not even be possible
    - *For example, suppose the PDF fits of the time simply have spreads that are inconsistent with better than a 25 MeV uncertainty.*
  - Personal view: given time, the LHC will be competitive and eventually outperform the Tevatron. I wouldn’t want to speculate on how much or how little time this would take, but it certainly won’t be one of the first results.

- Even after the Higgs is discovered, this measurement is important
  - Finding one Higgs is not necessarily the same as finding all of them.
  - Indirect constraints will be important in interpreting the discovery
What is the Standard Model?

The (Electroweak) Standard Model is the theory that has interactions like:

\[ W^+ + W^- + \gamma + Z^0 \]

but not:

\[ Z^0 + Z^0 + \gamma \]

Only three parameters - \( G_F \), \( \alpha \) and \( \sin^2(\theta_w) \) - determine all couplings.
The Semiclassical W

- Semiclassically, the interaction between the W and the electromagnetic field can be completely determined by three numbers:
  - The W’s electric charge
    - Effect on the E-field goes like $1/r^2$
  - The W’s magnetic dipole moment
    - Effect on the H-field goes like $1/r^3$
  - The W’s electric quadrupole moment
    - Effect on the E-field goes like $1/r^4$

- Measuring the Triple Gauge Couplings is equivalent to measuring the 2\textsuperscript{nd} and 3\textsuperscript{rd} numbers
  - Because of the higher powers of $1/r$, these effects are largest at small distances
  - Small distance = short wavelength = high energy
There are 14 possible $WW\gamma$ and $WWZ$ couplings

To simplify, one usually talks about 5 independent, CP conserving, EM gauge invariance preserving couplings: $g_1^Z$, $\kappa_\gamma$, $\kappa_Z$, $\lambda_\gamma$, $\lambda_Z$

- In the SM, $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$
  - Often useful to talk about $\Delta g$, $\Delta \kappa$ and $\Delta \lambda$ instead.
  - Convention on quoting sensitivity is to hold the other 4 couplings at their SM values.
- Magnetic dipole moment of the $W = e(1 + \kappa_\gamma + \lambda_\gamma)/2M_W$
- Electric quadrupole moment $= -e(\kappa_\gamma - \lambda_\gamma)/2M_W^2$
- Dimension 4 operators alter $\Delta g_1^Z, \Delta \kappa_\gamma$ and $\Delta \kappa_Z$: grow as $s^{1/2}$
- Dimension 6 operators alter $\lambda_\gamma$ and $\lambda_Z$ and grow as $s$

These can change either because of loop effects (think e or $\mu$ magnetic moment) or because the couplings themselves are non-SM
Why Center-Of-Mass Energy Is Good For You

- The open histogram is the expectation for $\lambda_\gamma = 0.01$
  - This is $\frac{1}{2}$ a standard deviation away from today’s world average fit

- If one does just a counting experiment above the Tevatron kinematic limit (red line), one sees a significance of 5.5$\sigma$
  - Of course, a full fit is more sensitive; it’s clear that the events above 1.5 TeV have the most distinguishing power

From ATLAS Physics TDR: 30 fb$^{-1}$
Qualitatively, the same thing happens with other couplings and processes.

These are from WZ events with $\Delta g_1^Z = 0.05$
- While not excluded by data today, this is not nearly as conservative as the prior plot
  - A disadvantage of having an old TDR
Not All W’s Are Created Equal

The reason the inclusive W and Z cross-sections are 10x higher at the LHC is that the corresponding partonic luminosities are 10x higher
  - No surprise there

Where you want sensitivity to anomalous couplings, the partonic luminosities can be hundreds of times larger.

The strength of the LHC is not just that it makes millions of W’s. It’s that it makes them in the right kinematic region to explore the boson sector couplings.

From Claudio Campagnari/CMS
Confession Is Good For The Soul

- There is a built-in swindle to this formalism

- Effects that grow as \( s^{\frac{1}{2}} \) or \( s \) are easy to see at large \( m(VV) \)
  - As \( m(VV) \) grows, these effects eventually violate unitarity
    - Of course those are easy to see! They're impossible to miss!

- It may be useful to think about turning this around
  - If there is new physics at high \( Q^2/\text{short distances} \), it can manifest itself at lower \( Q^2/\text{longer distances} \) as changes in the couplings: \( g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma \) and \( \lambda_Z \)
  - While the effects will be largest at high \( Q^2 \), they might not look like exactly like these predictions – it all depends on what this new physics is.

- NLO effects tend to increase the VV cross-section at high \( Q^2 \) – this reduces sensitivity somewhat.
## TGC’s – the bottom line

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Present Value</th>
<th>LHC Sensitivity (95% CL, 30 fb-1 one experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta g_1^Z$</td>
<td>$-0.016^{+0.022}_{-0.019}$</td>
<td>0.005-0.011</td>
</tr>
<tr>
<td>$\Delta \kappa_\gamma$</td>
<td>$-0.027^{+0.044}_{-0.045}$</td>
<td>0.03-0.076</td>
</tr>
<tr>
<td>$\Delta \kappa_Z$</td>
<td>$-0.076^{+0.061}_{-0.064}$</td>
<td>0.06-0.12</td>
</tr>
<tr>
<td>$\lambda_\gamma$</td>
<td>$-0.028^{+0.020}_{-0.021}$</td>
<td>0.0023-0.0035</td>
</tr>
<tr>
<td>$\lambda_Z$</td>
<td>$-0.088^{+0.063}_{-0.061}$</td>
<td>0.0055-0.0073</td>
</tr>
</tbody>
</table>

- Not surprisingly, the LHC does best with the Dimension-6 parameters
- Sensitivities are ranges of predictions given for either experiment
**Early Running**

- Reconstructing W’s and Z’s quickly will not be hard
- Reconstructing photons is harder
  - Convincing you and each other that we understand the efficiencies and jet fake rates is probably the toughest part of this

- We have a built in check in the events we are interested in
  - The Tevatron tells us what is happening over here.
  - We need to measure out here.
- At high $E_T$, the problem of jets faking photons goes down.
  - Not because the fake rate is necessarily going down – because the number of jets is going down.
Angular distributions have additional resolving power
  – Remember, the W decays are self-analyzing
  – Different couplings yield different angular distributions
    • Easiest to think about in terms of multipole moments

Neutral Gauge Couplings
  – In the SM, there are no vertices containing only γ’s and Z’s
  – At loop level, there are ~10^{-4} corrections to this
  – It is vital that these be explored
Quartic Couplings

- These are special – this is where the Higgs mechanism touches the Standard Model
- Signature is three bosons in the final state
- Yields are small, but not ridiculous
  - many dozens of events
  - this will not be an early measurement!
- It is difficult to generate a model where the trilinear couplings are at their SM values, but the quartics are not
  - It is still important to check
  - If something new is seen in the trilinears, one might need the quartics to sort things out.

<table>
<thead>
<tr>
<th>$M_{\text{Higgs}}$ (GeV)</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^-W^-$</td>
<td>68</td>
<td>28</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$W^+W^+W^-$</td>
<td>112</td>
<td>49</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>$W^+W^-Z$</td>
<td>32</td>
<td>17</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$W^-ZZ$</td>
<td>1.0</td>
<td>0.51</td>
<td>0.46</td>
<td>0.45</td>
</tr>
<tr>
<td>$W^+ZZ$</td>
<td>1.7</td>
<td>0.88</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>$ZZZZ$</td>
<td>0.62</td>
<td>0.18</td>
<td>0.13</td>
<td>0.12</td>
</tr>
</tbody>
</table>

From Azuelos et al. hep-ph/0003275

100 fb-1, all leptonic modes inside detector acceptance
**Top Production**

- Cross section determined to NLO precision
  - Total \( \sigma_{\text{NLO}}(tt) = 834 \pm 100 \) pb
  - Largest uncertainty from scale variation
- Compare to other production processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>N/s</th>
<th>N/year</th>
<th>Total collected before start LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>W→ev</td>
<td>15</td>
<td>10^8</td>
<td>10^4 LEP / 10^7 FNAL</td>
</tr>
<tr>
<td>Z→ee</td>
<td>1.5</td>
<td>10^7</td>
<td>10^7 LEP</td>
</tr>
<tr>
<td>tt</td>
<td>1</td>
<td>10^7</td>
<td>10^4 Tevatron</td>
</tr>
<tr>
<td>bb</td>
<td>10^6</td>
<td>10^{12-13}</td>
<td>10^9 Belle/BaBar \ ?</td>
</tr>
<tr>
<td>H (130)</td>
<td>0.02</td>
<td>10^5</td>
<td>?</td>
</tr>
</tbody>
</table>

**LHC is a top factory!**
Golden-plated: $M_{\text{Top}}$ from lepton+jet

- **Golden channel**
  - Clean trigger from isolated lepton

- The reconstruction starts with the W mass:
  - different ways to pair the right jets to form the W
  - jet energies calibrated using $m_W$

- Important to tag the b-jets:
  - enormously reduces background (physics and combinatorial)
  - clean up the reconstruction

**Typical selection efficiency: $\sim$5-10%:**
- Isolated lepton $P_T > 20$ GeV
- $E_T^{\text{miss}} > 20$ GeV
- 4 jets with $E_T > 40$ GeV
- $>1$ b-jet ($\varepsilon_b \approx 40\%$, $\varepsilon_{uds} \approx 10^{-3}$, $\varepsilon_c \approx 10^{-2}$)

**Background:** $<2\%$
- W/Z+jets, WW/ZZ/WZ

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$\text{Br}(tt\to bbjj\nu)=30\%$ for electron + muon
**Lepton + jet: reconstruct top**

- **Hadronic side**
  - W from jet pair with closest invariant mass to $M_W$
    - Require $|M_W - M_{jj}| < 20$ GeV
  - Assign a b-jet to the W to reconstruct $M_{\text{top}}$

- **Kinematic fit**
  - Using remaining l+b-jet, the leptonic part is reconstructed
    - $|m_{\ell b} - <m_{jjb}| < 35$ GeV
  - Kinematic fit to the tt hypothesis, using $M_W$ constraints

- Selection efficiency 5-10%
**Top mass systematics**

- **Method works:**
  - Linear with input $M_{\text{top}}$
  - Largely independent on Top $P_T$

- **Biggest uncertainties:**
  - Jet energy calibration
  - FSR: ‘out of cone’ give large variations in mass
  - B-fragmentation

- Verified with detailed detector simulation and realistic calibration

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**Challenge:**

determine the mass of the top around 1 GeV accuracy in one year of LHC
**Alternative mass determination**

- **Select high $P_T$ back-to-back top events:**
  - Hemisphere separation (bckgnd reduction, much less combinatorial)
  - Higher probability for jet overlapping

- **Use the events where both W’s decay leptonically (Br~5%)**
  - Much cleaner environment
  - Less information available from two $\nu$’s

- **Use events where both W’s decay hadronically (Br~45%)**
  - Difficult ‘jet’ environment
  - Select $P_T > 200$ GeV

*Various methods all have different systematics*
Top mass from $J/\psi$

- Use exclusive $b$-decays with high mass products ($J/\psi$)
  - Higher correlation with $M_{\text{top}}$
  - Clean reconstruction (background free)
  - $\text{BR}(tt\rightarrow qqb\ell\nu+J/\psi \rightarrow \ell\ell) \approx 5 \times 10^{-5}$
  - $\epsilon \sim 30\% \Rightarrow 10^3 \text{ ev./100 fb}^{-1}$ (need high lumi)

Different systematics (almost no sensitivity to FSR)

Uncertainty on the $b$-quark fragmentation function becomes the dominant error
Standard Model Higgs - Production and Decay

Higgs & Precision Electroweak @ LHC

A. Djouadi, J. Kalinowski, M. Spira

σ(pp → H+X)
√s = 14 TeV
m_t = 175 GeV
CTEQ4M

σ (pb)

M_H (GeV)

Higgs & Precision Electroweak @ LHC 9/29/08 J. Albert 30
Search Channels

- The easiest: \( H \rightarrow ZZ \rightarrow 4\ell \)
  - Four high \( p_T \) leptons and Z mass constraint

- The low-mass signal: \( H \rightarrow \gamma\gamma \)
  - 1% mass resolution
  - Background from sidebands
Search Channels

- in the most promising mass range: $VBF\ \bar{q}q \rightarrow V^*V^*\bar{q}q \rightarrow H\bar{q}q \rightarrow WW\bar{q}q / \tau\bar{q}q$

Forward jet tagging
Central jet veto
→ reduced background

10% mass resolution
Careful with NLO corrections to \( gg \rightarrow H \) → reduced significance

Most interesting mass range → many channels to combine!
## Strategy for First Data

- background and reconstruction studies → discovery!

<table>
<thead>
<tr>
<th>Process</th>
<th>10 pb⁻¹</th>
<th>100 pb⁻¹</th>
<th>1000 pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ \rightarrow llll$</td>
<td>Lepton id</td>
<td>?signal?</td>
<td>Signal</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow llll$</td>
<td>Drell-Yan, top</td>
<td>?signal?</td>
<td>Signal</td>
</tr>
<tr>
<td>VBF $H \rightarrow \tau\tau$</td>
<td>Top studies</td>
<td>$Z$</td>
<td>Signal?</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>Background, jet/γ</td>
<td>?signal?</td>
<td></td>
</tr>
<tr>
<td>$ttH \rightarrow ttbb$</td>
<td>Top studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invisible Higgs</td>
<td>Background, trigger</td>
<td>???</td>
<td></td>
</tr>
<tr>
<td>Charged Higgs</td>
<td>?top?</td>
<td></td>
<td>Signal</td>
</tr>
<tr>
<td>$h/H/A \rightarrow \mu\mu$</td>
<td>Top study</td>
<td>?signal?</td>
<td>Signal</td>
</tr>
<tr>
<td>$h/H/A \rightarrow \tau\tau$</td>
<td>Z, top studies</td>
<td></td>
<td>Signal</td>
</tr>
</tbody>
</table>
**Higgs Spin and CP**

- in SM: Higgs is $0^{++}$
- measure spin and CP in H decay
- easiest in $H \rightarrow ZZ \rightarrow 4\ell$

![Graph showing mass of off-shell Z](graph.png)
Higgs Spin and CP

- ZZ decay plane correlations
- for 100 fb

Decay plane angle + fermion angle in Z rest frame

Higgs Spin and CP
Higgs & Precision Electroweak @ LHC

9/29/08 J. Albert
**Higgs Spin and CP**

- measurement of $H \to ZZ$ couplings

- spin-0 case:

\[
i \frac{g M_Z}{\cos \theta_W} \left[ A g_{\mu\nu} + B p_{\mu} p_{\nu} + C \epsilon_{\mu\nu\rho\sigma} p^\rho k^\sigma \right]
\]

**SM**

$CP^+$  $CP^-$

![Plot of fit to SM input with 68% and 95% C.L. contours](image-url)
**tth Higgs CP Determination**

- From Gunion, He (PRL 76, 24, 4468 (1996)):

  Interaction Lagrangian:
  (c is CP-even coupling and d is CP-odd)
  \[ \mathcal{L} \equiv \bar{t}(c + i d \gamma_5) t h \]
  SM: c=1, d=0

  **CP-sensitive variables:**
  \( p_T \) of Higgs, or missing \( p_T \) from partial
  reconstruction can be **substituted** for \( p_T \) of
  second top.

  \[
  \begin{align*}
  a_1 &= \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_t \times \hat{n})}{| (\vec{p}_t \times \hat{n}) \cdot (\vec{p}_t \times \hat{n}) |} \\
  a_2 &= \frac{p_t^x p_t^x}{| p_t^x p_t^x |} \\
  b_1 &= \frac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_t \times \hat{n})}{p_t^T p_t^T} \\
  b_2 &= \frac{p_t^z p_t^z}{| p_t | | p_t^z |} \\
  b_3 &= \frac{p_t^x p_t^x}{p_t^T p_t^T} \\
  b_4 &= \frac{p_t^z p_t^z}{| p_t | | p_t^z |}
  \end{align*}
  \]

- With the increased efficiency from single top reconstruction, sensitivity can likely be obtained with 100-200 fb\(^{-1}\) of data.
CP-sensitive variables:

\[
a_1 = \frac{(\vec{p}_t \times \vec{n}) \cdot (\vec{p}_t \times \vec{n})}{||\vec{p}_t \times \vec{n}||^2 / \vec{p}_t \cdot \vec{p}_t^*} \quad b_1 = \frac{\vec{p}_t \times \vec{n}}{||\vec{p}_t|| \vec{p}_t} \quad b_2 = \frac{(\vec{p}_t \times \vec{n}) \cdot (\vec{p}_t \times \vec{n})}{||\vec{p}_t \times \vec{n}||^2 / \vec{p}_t \cdot \vec{p}_t} \quad b_3 = \frac{\vec{p}_t \times \vec{n}}{||\vec{p}_t|| \vec{p}_t}
\]

Partial Reconstruction: \( p_T \) of Higgs can be substituted for \( p_T \) of one of the tops:

(Gunion & He, PRL 76, 4468 (1996))
qqh VBF Higgs CP Determination

- Two hard tagging jets
- Two central b jets

Distributions of the difference in azimuthal angle ($\phi$) between the two quark jets in fully reconstructed vector boson fusion $qqh, h \rightarrow bb$ events:

SM Higgs

CP-odd Higgs

Looks to be promising, for the difficult low mass region for Higgs properties measurement
**Magnet Failure**

- Fault in sector 3-4 on 19 Sept. thought to possibly be located in busbar in interconnect btw. two dipoles
- Occurred during commissioning of dipole fields to 5.5 TeV level
- Cryostat and vacuum vessel wall breached, between 1-2 tonnes of He were vented to the tunnel

### Busbars

The superconducting magnets are connected in series with highly copper stabilised superconducting cables (busbars). The ratio of the copper fraction to the superconductor content is usually greater than 10 to reduce the probability of a quench originating in the busbars. The copper stabilisation is possible for busbars as more space is available than in magnet coils. It is required to avoid overheating after a quench as the busbars are only protected by dump resistors for energy extraction and not by parallel elements as for magnets. For the LHC superconducting circuits, several types of busbars are foreseen:

- **main busbars**
  
  For the main dipole magnets and the arc quadrupoles, the busbars will carry a current up to 13kA. These busbar are made with the superconducting cable used to wind the outer layer of the dipole magnets and the arc quadrupoles. The cable is soldered in a copper housing (see Fig 1.12). The copper stabilisation for the dipole circuits is in the order of 250mm$^2$ and for the quadrupole circuits in the order of 160mm$^2$.

![Diagram of LHC Dipole: Standard Cross-Section](image)

*Copper stabilisation*

*Rutherford cable*

**Figure 1.12:** Schematic diagram of the busbar cross-section for the LHC main

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*Hopefully April ’09 will be less cruel...!!!*